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China's energy transition strategy at the city level: The role of renewable energy

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ABSTRACT

Renewable energy plays a significant role in climate change mitigation and energy transition. China has established demonstration cities for energy transition and renewable energy development. However, the assessment system for these implementations is relatively blank. This study develops an index system to guide the construction of energy transition demonstration project and optimize energy transition development at the city level. The genetic algorithm-based analytic hierarchy process is employed to form energy transition strategies in the cities of Guiyang, Tongren, Zhangjiakou, and Nanning. The priority values of different renewable energy technologies are given for the cities. The results show that resource endowment is not the only driver for the priority due to the unique combination of influence factors in decision. The assessment system can help avoid the problems of single operating mode and over-investment in the process of energy transition so as to find the benchmark for energy structure adjustment. Finally, some policy recommendations are made for city-scale energy transition.

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1. Introduction

Energy transition is of great importance in city development (Coelho et al., 2018; Huang et al., 2018; Mi et al., 2015, 2016). The renewable energy system for a nearly zero greenhouse city is required in the future smart society (De Luca et al., 2018; Yuan et al., 2017). The National Energy Administration of China released the 13th Five-Year Plan of renewable energy development in 2016. It states that various types of renewable energy demonstration should be made in the appropriate areas, which could provide lessons for power market construction and power system reform. In order to promote renewable energy deployment and increase the percentage of renewable energy consumption, the demonstration project for energy transition needs to be constructed in different regions. A city is the main carrier of economic development and energy consumption. An important way to achieve China's sustainable development is to reduce the proportion of fossil fuels and build a renewable and sustainable energy system in the cities. Therefore, it is necessary to timely examine and assess city-scale renewable energy utilization.

China has launched a series of documents on renewable energy development at the city level. Up till now, there are 36 low-carbon pilot cities, 81 new energy model cities, and 8 new energy industrial parks. Many studies have investigated the construction of renewable energy system in the cities. The relationship between urbanization and renewable energy development is critical (Bao and Fang, 2013; Yang et al., 2016). Arenas-Aquino et al. (2017) discussed the promotional effects of solar utilization in urban development. The potential of solar resource is evaluated for city development in Turkey (Usta et al., 2017). Brito et al. (2017) made comparative analysis of cities by introducing compressed natural gas to urban bus fleet. Adam et al. (2016) developed a method to assess city-scale renewable energy generation potential for strategic energy infrastructure investment. Also, some other examples have been studied for urban energy transition, such as technical

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geothermal potential (Rivera et al., 2017), district heating integration (Unternahrer et al., 2017), and thermal geological model (Soriano et al., 2017). Some scholars questioned the nexus between energy transition, water, and climate, and doubted how natural gas can be included in urban energy transition (Osorio-Tejada et al., 2017). Yuan and Zhong (2010) analyzed the international experience of constructing urban low-carbon energy system and put forward some practical opinions on China's low-carbon city construction.

However, the literature only focuses on a specific type of renewable energy for the development and utilization in city planning. There are few studies on the quantitative evaluation on renewable-based energy transition system for cities (Woldeyohannes et al., 2016). The current renewable energy utilization index system in China aims to promote the development of renewable energy industry. It clarifies the definition and scope of renewable energy in the city and just takes the proportion of renewable energy consumption as a key indicator. Obviously, such index system is difficult to provide basis and guidance for renewable energy development since it overemphasizes on the amount of consumption. The overall city planning, social and environmental benefits, returns of investment, and so on have not been considered in the previous studies. The policy implications revealed by these researches cannot fully target on China's sustainable development.

It is a crucial issue that how to decide the renewable-based energy transition considering multidimensionality (Kumar et al., 2017). Multi-criteria decision methods are able to select the best options from the alternatives. Notably, the weights of the criteria play an important role in decision making (Sierra et al., 2018). The subjective weight is commonly determined by subjective judgement, while the objective weight is directly drawn from the data of alternatives (Lee and Chang, 2018). As energy development highly relies on expert experience and insights, many researches employ the analytic hierarchy process (AHP) for decision making (Blanco et al., 2017; Haddad et al., 2017; Kaya et al., 2018). The preferences are made by pairwise comparison matrices within a hierarchical structure of different criteria. Importantly, the consistency of comparison matrix is a key point in the practical application of AHP, and the small consistency indicates accurate weights. Accordingly, a consistency index function is developed (Jin and Wei, 2008; Zhao et al., 2016), and is minimized to obtain the associated weights. Since traditional methods have difficulty in solving nonlinear programming, the intelligent technique such as genetic algorithm is more suitable for optimizing consistency index function. In this way, the genetic algorithm-based AHP is used in our analysis to measure the development priority of alternative renewable energy types in the cities.

There is a need of proper framework for arranging different types of renewable energy technologies in energy transition. Renewable energy development needs to be considered in China's low-carbon transition with the theory and practice from the pioneer cities and transition cities (Nagorny-Koring and Nochta, 2018; Wang et al., 2018). This study attempts to propose an index system to measure energy transition with a focus on renewable energy development at the city level in China, and explores the optimal development path of energy transition. Due to China's 'new normal' economic development and excess electricity capacity, this index system takes macroeconomic planning, city development orientation, and resource endowment into account. The energy utilization is divided into four categories, and then the energy transition is evaluated. The priority of different renewable energy technologies are calculated by the genetic algorithm-based analytic hierarchy process to provide the basis and guidance for energy transition development. Optimal strategies are put forward to direct renewable energy deployment in the cities.

2. Index system for energy transition strategy

Energy utilization is divided into electricity (hydropower, wind power, photovoltaic, thermal power, and biomass power), gas supply (pipeline natural gas and unconventional gas), heat supply (solar water heater and geothermal energy building), and fuel (biomass briquette fuel and biomass liquid fuel). In addition, the energy transition index system are developed with the dimensions of overall harmony strategy, amount of fossil energy substituted, investment in renewable energy, and cost of fossil energy substitution. Accordingly, the priority of these indicators is calculated by the genetic algorithm-based AHP. The suitable type of renewable energy and development priority are suggested.

This study considers four eligible forms of energy utilization including electricity, gas supply, heat supply, and fuel. First, renewable energy is converted to electricity and integrated into grid, including hydropower, wind power, photovoltaic, thermal power, biomass power, and trash to energy, which are the most important ways of renewable energy use. Second, national gas supply takes pipeline natural gas as main source while biological gas, shale gas, and coal-bed methane as supplemental source. Third, the combination of heat and power as well as concentrated heating would be a primary channel to satisfy public heat demand. Further, the gases are supplied to household, public building, and industry. Heat supply converts renewable energy into heat, mostly in the way of solar water heater and geothermal energy building. Finally, renewable fuels are used directly in the form of biomass briquette/liquid fuel and ethanol fuel, and biodiesel is a major form of liquid fuel for transportation.

2.1. Overall harmony strategy

Overall harmony strategy is an indicator with a special consideration for city planning. Sustainable development and low-carbon transition actions should account for the overall harmony with long-term city development plan (Hukkalainen et al., 2017; Torabi Moghadam et al., 2017). It is crucial to select renewable energy type and decide development mode and capacity for the construction of energy transition in the city. According to the orientation of city, it is supposed to consider economic development, social progress, and environment protection on the basis of city characteristics, city development, and city area. That is, energy transition strategy in the city needs to be created in accordance with the overall city planning.

2.2. Amount of fossil energy substituted

This indicator could represent the historic responsibility for a city to take actions in energy transition and it is regarded as one of the most important factors for renewable energy deployment. According to the projection by National Energy Administration of China, the energy transition model city is supposed to have a high share of renewable energy in total energy consumption. Therefore, it is essential to measure the amount of alternative fossil fuels for the development and utilization of renewable energy. Urbanization rate is expected to reach 60% by 2020, and it is more likely to develop renewable energy that could replace more fossil energy.

2.3. Investment in renewable energy

The action towards energy transition needs investment in these projects. Thus, the investment in renewable energy has been selected as an indicator to represent the economic ability to enact energy transition strategy. It is predicted that by 2020 there would be an increment of 60 GW in hydropower with the investment of

500 billion CNY (Chinese Yuan), and 80 GW in wind power with the investment of 700 billion CNY. Accounting for solar energy, biomass power, biogas, and geothermal energy, the total investment in renewable energy would be around 2.5 trillion CNY during the 13th Five-Year Plan of China. Thus, the investment is of significance for renewable energy development. Al-mulali et al. (2013) examined the bi-directional long-run relationship between renewable energy consumption and gross domestic product (GDP) growth. Asafu-Adjaye (2000) analyzed the relationship between energy consumption, energy prices and economic growth in Asian developing countries. These studies suggest that 79% of the countries have a positive bi-directional long-term relationship between renewable energy consumption and GDP growth, and for higher income countries there are more persistent and significant bi-directional long run relationship between renewable energy consumption and GDP growth.

2.4. Cost of fossil energy substitution

Cost of fossil energy substitution determines the expense of energy transition and the technology choice for clean energy systems. This indicator emphasizes the quality and efficiency in the development process of energy transition model city. The orientation, advantage, and investment benefit are usually considered to promote sustainable city development. For example, many cities in China aim to adjust energy structure by taking natural gas as the key component in the medium or long term plan of energy supply. However, industrial use of natural gas encountered many problems, such as higher price, absorption of imported gas, scarcity of supplies, and so on. Thus, the cost of fossil energy substitution serves as an indicator for the cost effectiveness of energy transition.

3. Method

The AHP (Saaty, 1980) is widely used to obtain weights by pairwise comparison, and the consistency of comparison matrix is of significance for weight calculation. Here the genetic algorithm-based analytic hierarchy process is employed to ensure the accuracy of weight.

Step 1: The relative importance of indicator u compared with v is denoted by a_{uv} ($u = 1,2, \ldots, t$; $v = 1,2, \ldots, t$), so the comparison matrix $\boldsymbol{A} = (a_{uv})_{t\times t}$ is formed. If u is more important than v, the value of relative importance ranges from 1 to 9 (Table 1). Otherwise, the associated reciprocal values are taken. The bigger value indicates greater importance. The pairwise comparison matrix of indicators for energy transition strategy is shown in Table S1 (supplemental material), and those of alternative energy types for different indicators are shown in Table S2-Table S5.

Step 2: Suppose the weights of indicator u and v are W_u and W_v. If the relative importance of indicators could be exactly measured (i.e. $a_{uv} = W_u/W_v$), then the following equations are obtained (Zhao et al., 2016).

Table 1
Measurement of relative importance.

Score	Definition
1	Equally important
3	Moderately important
5	Strongly important
7	Very strongly important
9	Extremely important
2,4,6,8	Between 1,3,5,7,9

$$\sum_{v=1}^{t} a_{uv}W_v = \sum_{v=1}^{t}(W_u/W_v)W_v = tW_u \tag{1}$$

and

$$\sum_{u=1}^{t}\left|\sum_{v=1}^{t} a_{uv}W_v - tW_u\right| = 0 \tag{2}$$

Normally, a_{uv} has the deviation in measuring the ratio of W_u to W_v due to the complex cognition in reality. The smaller value of the left term in Eq. (2) indicates the greater consistency. Thereby, the consistency index function (CIF) shown in Eq. (3) is developed to check whether the pairwise comparison matrix is acceptable (Jin and Wei, 2008).

$$\begin{aligned} &\mathrm{CIF} = \sum_{u=1}^{t}\left|\sum_{v=1}^{t} a_{uv}W_v - tW_u\right| \Big/ t \\ &\text{s.t.} \quad \sum_{u=1}^{t} W_u = 1 \end{aligned} \tag{3}$$

Step 3: In order to obtain minimum CIF which means higher consistency, we employ genetic algorithm to minimize Eq. (3). If the value of CIF is less than 0.1, the pairwise comparison matrix is considered to be consistent and the calculated weights $\boldsymbol{W}$ are acceptable.

4. Study area

The National Energy Administration of China has announced a list of model and pilot cities (parks) of new energy utilization. Here, some of them as well as the potential city are selected for this study. They have obvious differences in city positioning, energy resource endowment, and utilization type, and thus it can demonstrate the rationality of renewable energy development index system.

4.1. Guiyang

Guiyang is the capital of Guizhou and a major city in Southwest China. As the provincial center, it is also the transportation and communication hub, industrial base, and tourist center of Southwest China. Its energy supply mainly comes from other regions, and self-sufficiency rate of primary energy was 13%–18% during 2009–2016. The key point of its energy transition is to ensure energy supplies and increase renewable energy consumption. The overall plans of Guiyang show that pipeline natural gas and clean transportation are essential during the 13th Five-Year Plan period.

4.2. Tongren

It is a city of Guizhou province with surplus electric power supply capacity. Yet, its coal and oil rely on the supply from other regions. The renewable energy consumption in Tongren is relatively small, but water source heat pump and ground source heat pump have been widely used. Hydropower and biomass energy are the main types of renewable energy which account for 84.9% and 10.9% respectively. Biomass power generation and biogas are primary sources for biomass energy utilization that are determined by government support and biogas construction. The overall city plans of Tongren show that water source heat pump and ground source

heat pump are key roles in the 13th Five-Year Plan period. Even though it is not selected in the list of pilot cities for new energy utilization, we include it in this study because of its ongoing push toward 100% renewable energy in the city.

4.3. Zhangjiakou

It is a city of Hebei province with abundant wind resource and solar resource in North China, and listed in the national new energy bases. There are more than 40 million kilowatts of wind energy potential and more than 30 million kilowatts of solar energy potential. The renewable energy demonstration plan shows that this city would focus on wind power and photovoltaic and promote thermal power actively. The future work is to construct the decentralized wind farms near city center, and develop wind power heating to replace coal-fired boiler. Due to its importance in renewable energy demonstration, the National Development and Reform Commission of China released individual plan for Zhangjiakou to explore the new mechanism of renewable energy deployment in electricity, heating, transport, building, and so on.

4.4. Nanning

As the capital of Guangxi province, it is the main grain-producing area and economic crop cultivation base. The new energy industrial plan aims to develop biomass fuels, and promote the comprehensive utilization of biomass energy with papermaking, sugar making, and brewing industry (e.g. the production of ethanol fuel from cassava, grain, and other starch raw materials, the production of biodiesel from agricultural raw materials, and the production of biogas and fuels from cassava straw, mulberry, and sugar cane leaves). Its plan for renewable energy development is ambitious in wind power, solar power, and biomass.

5. Results

5.1. Energy transition strategies in the cities

At present, there is smaller growth rate of economy, power consumption, and energy consumption in China. As environmental constraints become more and more serious, renewable energy will play an important role in the structure of energy production and consumption. Meanwhile, China will accelerate the development of geothermal energy, biogas, biomass energy heating, solar water heater, and other non-electric utilization. The indicator weights for energy transition are shown in Table 2. It can be found that overall harmony strategy and amount of fossil energy substituted are of the same importance. Furthermore, the investment in renewable energy has bigger weight than cost of fossil energy substituted. It means that the increment of renewable energy is essential for energy transition, and renewable energy development needs to be concordant with the entire city planning. The lower weight of technology cost occurs in the demonstration phase, and it should not be overstated in the promotion stage.

According to each indicator, the importance of different types of renewable energy is compared (Table 3). For example, in the perspective of overall harmony strategy in Guiyang, gas supply has higher priority than other types of renewable energy. However, in the perspective of investment in renewable energy the top priority is given to electricity. Heat supply could have prior development in view of cost of fossil energy substitution.

On the basis of weights in Tables 2 and 3, the priority values of renewable energy for the cities are calculated as Table 4. The four cities have their own characteristics, so that there are different renewable energy development strategies. Gas supply should be under consideration prior to other renewables for Guiyang. Yet, heat supply seems better for Tongren. Besides, electricity and fuel are more suitable for Zhangjiakou and Nanning respectively.

Table 2
Weights of the indicators for energy transition strategy.

Indicators	Weights
Overall harmony strategy	0.351
Amount of fossil energy substituted	0.351
Investment in renewable energy	0.189
Cost of fossil energy substitution	0.109

Table 4
Priority values of different energy for the cities.

Energy types	Priority values			
	Guiyang	Tongren	Zhangjiakou	Nanning
Electricity	0.199	0.204	0.482	0.196
Gas supply	0.370	0.240	0.177	0.251
Heat supply	0.214	0.365	0.175	0.120
Fuel	0.217	0.191	0.166	0.433

Table 3
Weights of different types of renewable energy.

Cities	Indicators	Electricity	Gas supply	Heat supply	Fuel
Guiyang	Overall harmony strategy	0.112	0.358	0.229	0.301
	Amount of fossil energy substituted	0.143	0.460	0.157	0.240
	Investment in renewable energy	0.472	0.285	0.170	0.073
	Cost of fossil energy substitution	0.190	0.269	0.420	0.121
Tongren	Overall harmony strategy	0.109	0.351	0.351	0.189
	Amount of fossil energy substituted	0.160	0.095	0.467	0.278
	Investment in renewable energy	0.472	0.285	0.170	0.073
	Cost of fossil energy substitution	0.190	0.269	0.420	0.121
Zhangjiakou	Overall harmony strategy	0.464	0.144	0.189	0.203
	Amount of fossil energy substituted	0.522	0.136	0.162	0.180
	Investment in renewable energy	0.472	0.285	0.170	0.073
	Cost of fossil energy substitution	0.430	0.231	0.176	0.163
Nanning	Overall harmony strategy	0.136	0.280	0.114	0.470
	Amount of fossil energy substituted	0.227	0.227	0.122	0.424
	Investment in renewable energy	0.227	0.227	0.122	0.424
	Cost of fossil energy substitution	0.233	0.277	0.125	0.365

5.2. Sensitivity analysis

Since the weights are highly influenced by the pairwise comparison matrix which gives relative importance between indicators and alternatives, there is a need to check the robustness of the outcomes calculated by the genetic algorithm-AHP. For the sensitivity analysis, a change in relative importance of pairwise comparison matrix is allowed to range between −50% and 50%. Accordingly, we generate 100 random changes for each pairwise comparison matrix so as to obtain the associated weights. The newly developed weights are averaged to calculate priority values. Table 5 shows similar suggestions for the renewable energy development strategies in four cities.

Table 5
Sensitivity analysis for priority values.

Energy types	Priority values			
	Guiyang	Tongren	Zhangjiakou	Nanning
Electricity	0.141	0.166	0.414	0.152
Gas supply	0.429	0.255	0.197	0.272
Heat supply	0.202	0.356	0.168	0.105
Fuel	0.228	0.223	0.221	0.471

5.3. Relationships between development priority and available amount of renewable energy

We also explore the relationships between development priority and available amount of renewable energy for the cities (shown as Fig. 1). Here the share of each type of renewable energy in total energy supply is used. It can be found that there are negative relationships in the cities of Guiyang and Tongren. Electricity accounts for a higher share in the two cities, but it seems not to be the best choice. There will be a transmission pipeline project of natural gas supplied from Burma in Guizhou, so it is more appropriate for Guiyang to develop gas supply. Due to the dense streams and rivers in Tongren, the development of water source heat pump is more suitable. As a result, renewable energy development needs to mainly consider the overall city planning.

The positive relationships are found in Zhangjiakou and Nanning. It means that the abundant resources have the top development priority. The wind and solar energy is abundant in China, and the technologies for them are relatively mature. Presently, the process of energy transition is still on the basis of renewable energy for power generation that is the main way to decrease fossil energy consumption. In the context of electricity supply surplus, the gas, heating, and clean fuel applications would be widely developed according to China's long-term planning. In practice, the energy

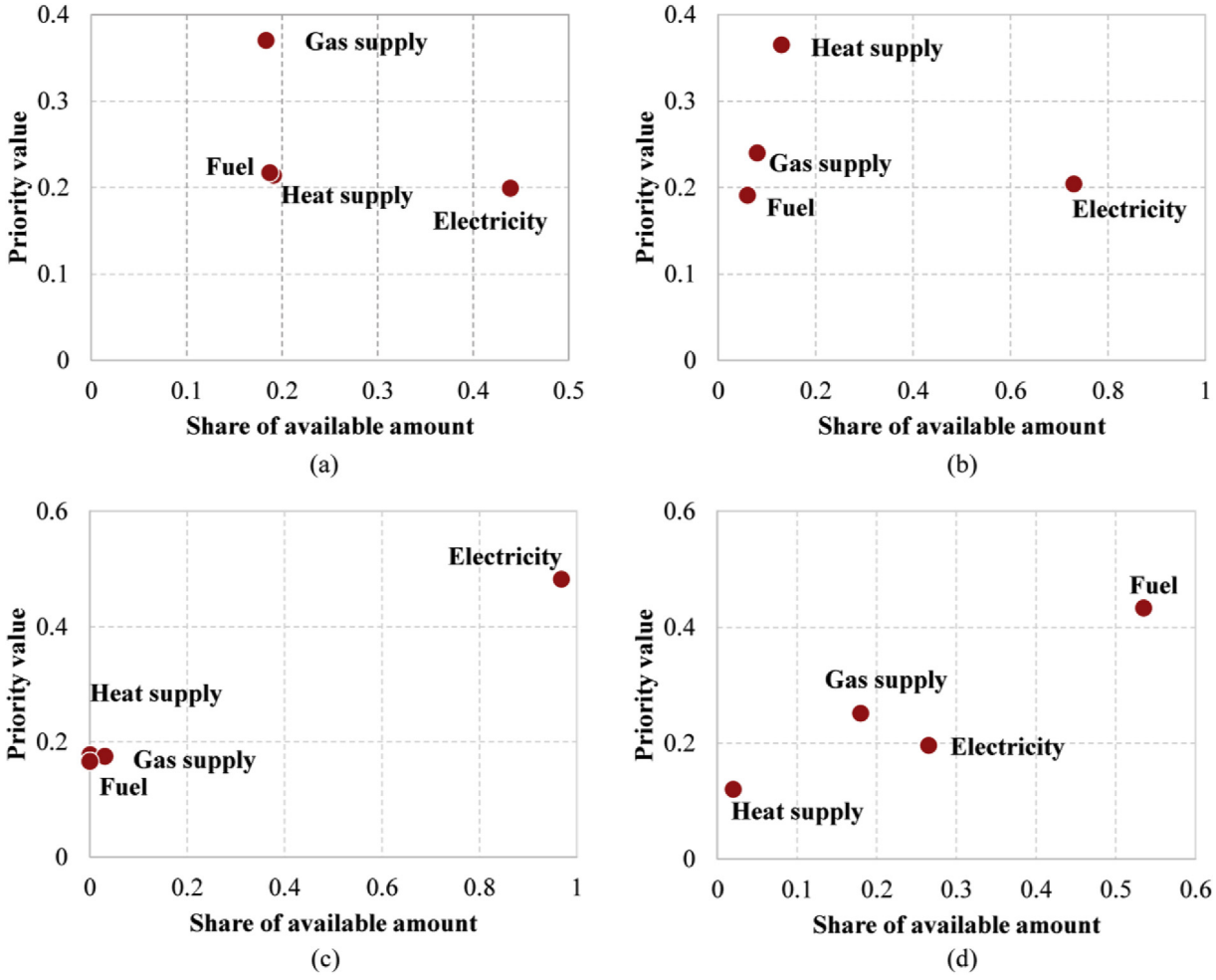

Fig. 1. Relationships between development priority of renewable energy and share of available amount of renewable energy in the cities of (a) Guiyang, (b) Tongren, (c) Zhangjiakou, and (d) Nanning.

transition process in the city is strongly influenced by national and city policies. Gas supply and renewable energy-heating would play a significant role in the process of construction of energy transition model city. However, the conventional natural gas industry in China is faced with many problems such as inadequate domestic exploration, high price of imported contract gas, pipeline construction, urban and rural planning contradiction, and so on.

6. Discussion

The previous evaluation index system for developing renewable energy model city pays more attention to the share of renewable energy consumption in the total. However, it actually ignores the overall city planning, social benefits, ecological benefits, return on investment, and some other factors (Table 6). As a result, it is improper to guide the renewable energy development at the city level. There are eight suggested indicators for the construction of low-carbon eco-city (Cao and Li, 2011; de Jong et al., 2016; Zhou et al., 2015) which are labor and employment, GDP contribution, project profitability, land acquisition, social identity, greenhouse gas emissions, environmental pollution, and unit investment ratio. The priority value is a comprehensive combination of economic, social and ecological factors. The point is the priority values of evaluation indicators for different city are not fixed. Based on the national urbanization construction, the Chinese government's commitment to energy conservation and emission reduction at the Paris Climate Conference, and the growth of national GDP driven by renewable energy industry, this paper put forward four evaluation indicators at the present stage, including overall harmony strategy, amount of fossil energy substituted, investment in renewable energy, and cost of fossil energy substitution.

China issued a notice to adjust the benchmark price of photovoltaic power generation and onshore wind power in 2016. The downward adjustment of the benchmark price directly affects the enthusiasm of project owners. The scale of renewable energy installed capacity is also affected. On the other hand, in order to solve the problem of relative surplus of electricity supply, the creation of energy transition model city focuses on gas supply, heat supply, and renewable energy fuel. However, due to the imperfection of China's gas pipeline, heating pipeline, clean energy transportation, and other infrastructure construction, this lagging infrastructure may result in higher risk of investment in such projects.

The primary principle for energy transition model city is to coordinate with the overall city planning. Besides, the proportion of renewable energy consumption should achieve a relatively high level for energy transition model city. The National Energy Administration clarified the scope of urban renewable energy in 2012. There are ten kinds of renewable energy, including solar heat utilization, photovoltaic generation, wind power, ground source heat pump, garbage power, generate electricity for biomass combustion, fuel ethanol, biodiesel, briquettes fuel, and biogas engineering. They are divided into four categories in this paper (i.e. electricity, gas supply, heat supply, and fuel) in order to calculate the priority of energy transition evaluation system. This will help provide a more simple and effective decision-making reference for city development. It should be noted that natural gas is not renewable energy, but high quality, efficient, and low-carbon fossil energy. Natural gas could be complementary with nuclear energy, renewable energy, and other low-emission energy. Thus, it is an important factor in the creation of energy transition model city, and needs to be emphasized in energy transition.

Table 6
Comparison of the evaluation indexes for energy transition.

Indicators	Proposed index of this study	Current index in practice
Overall harmony strategy	X	X
Amount of fossil energy substituted	X	X
Investment in renewable energy	X	–
Cost of fossil energy substitution	X	–

7. Conclusions

During the 13th Five-Year Plan period, China will build a number of regional energy transition model projects. The renewable energy utilization index is designed to guide the construction of energy transition model city. The AHP method based on genetic algorithm is used to calculate the renewable energy development priority.

The proposed index can be employed for the development priority of renewable energy utilization in the cities of China. The limitation lies in the problem that there is no one-time solution to the specific development projects. To determine a city's renewable energy development projects and the overall scale is relatively complex. Therefore, it is more practical and effective to study the priority of renewable energy type. The highest priority of energy types for Guiyang, Tongren, Zhangjiakou, and Nanning are gas supply, heat supply, electricity, and fuel, respectively. The priority of renewable energy development is the direct embodiment of city energy planning to serve urban overall planning. The weights of indicators are subjective, and there needs to be different plans for the cities. Besides, the positive relationship between priority value of renewable energy utilization and available amount of renewable energy is found in Zhangjiakou and Nanning. At the present stage, city-scale energy transition process is strongly influenced by national and city policies.

In the next period, energy transition model city will focus on the integrated and coordinated control of photovoltaic, wind power, distributed energy storage, megawatt micro-grid, electric vehicle, cooling-heating-power cogeneration, flexible load, and so on. The ultimate goal is to achieve the centralized and rational allocation and consumption of energy, improve energy efficiency, and make more efficient operation of power grid. More importantly, it is highly recommended to set up a demonstration area. If the pilot project operates well, it can be promoted within the whole city. Renewable technologies in the heating and cooling and transport sectors need to be further developed, and the renewable generation needs to be integrated into national power grid.

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Appendix A. Supplementary data

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